A Low-Cost Wireless System for Autonomous Generation of Road Safety Alerts

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ABSTRACT

This paper describes an autonomous wireless system that generates road safety alerts, in the form of SMS and email messages, and sends them to motorists subscribed to the service. Drivers who regularly traverse a particular route are the main beneficiaries of the proposed system, which is intended for sparsely populated rural areas, where information available to drivers about road safety, especially bridge conditions, is very limited. At the heart of this system is the SmartBrick, a wireless system for remote structural health monitoring that has been presented in our previous work. Sensors on the SmartBrick network regularly collect data on water level, temperature, strain, and other parameters important to safety of a bridge. This information is stored on the device, and reported to a remote server over the GSM cellular infrastructure. The system generates alerts indicating hazardous road conditions when the data exceeds thresholds that can be remotely changed. The remote server and any number of designated authorities can be notified by email, FTP, and SMS. Drivers can view road conditions and subscribe to SMS and/or email alerts through a web page. The subscription-only form of alert generation has been deliberately selected to mitigate privacy concerns. The proposed system can significantly increase the safety of travel through rural areas. Real-time availability of information to transportation authorities and law enforcement officials facilitates early or proactive reaction to road hazards. Direct notification of drivers further increases the utility of the system in increasing the safety of the traveling public.

Keywords: structural health monitoring, alert generation, road safety, wireless sensor network, remote monitoring, low power consumption.

1. INTRODUCTION

The diversity of road hazards complicates the design of related alert systems, especially where autonomy is concerned. Safety hazards on roadways can be attributed to two main sources: 1) motorist error or vehicle malfunction, and 2) natural phenomena or infrastructure failure. The safety alert system proposed in this paper seeks to mitigate hazards arising from the second category, which includes phenomena such as flooding and bridge collapse. The system is autonomous, which is particularly beneficial in sparsely populated rural areas with scarce resources available for monitoring road conditions. Structural and environmental monitoring, with the means of connecting to the cellular network, play the instrumental roles in the safety alert system.

This paper describes an autonomous, wireless system which generates safety alerts to motorists. The system utilizes a wireless sensor network to collect data about certain key parameters of a bridge and its surroundings, including: tilt, vibration, acoustic emissions, temperature, and water level. The data from the sensor network is relayed to the SmartBrick, a structural health monitoring device developed by the authors and presented in previous publications.\textsuperscript{1,2}

The SmartBrick serves as the base station and data sink for the sensor network, and is responsible for processing and reporting of the collected data. The device has an onboard quad band modem, which allows it to connect to the cellular network for regular communication of data reports and alerts to multiple recipients. Earlier prototypes of the system could be configured to report by one or more of FTP, text messaging, and email. The recipients of these reports were a remote server, the system administrators, and any authorities responsible

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for carrying out safety measures such as closing a bridge during flash flooding. In this paper, we describe an
extension to the original system that allows the general public to subscribe to email or text message alerts for a
given region.

The utility of the proposed system is increased to multi-span bridges through the use of a wireless sensor
network. Multiple sensor nodes are deployed on the bridge and surrounding area, and communicate wirelessly
with a single SmartBrick that serves as the base station and gateway for long-range communication over the
cellular phone infrastructure. Short-range communication among the sensor nodes, and between the sensor
nodes and the base station is implemented using the Zigbee protocol. This low-cost and unobtrusive method for
monitoring a large area is particularly well-suited for sparsely populated rural areas, where information available
to drivers about road safety, especially bridge conditions, is very limited. This paper details the design and
implementation of the resulting alert generation system, which carries the promise of increased safety for the
traveling public.

2. RELATED WORK

Early warning road safety systems are invaluable in alerting motorists to adverse situations on the roadways.
Such systems have contributed to the prevention of major accidents, reduction in injuries and casualties, and a
populace conditioned to respond to alerts. The ongoing need for a reliable and efficient alert system for early
warning of hazardous road conditions has prompted numerous related studies, which vary significantly in their
applications to road safety and implementation of necessary functions. A number of salient contributions are
described in the following paragraphs.

Basha, et al. have proposed the use of a wireless sensor network for environmental predictions. Specifically,
the system is used to provide early warning of flooding using a predictive model. The system is designed to be
robust, in order to withstand environmental exposure in flood-free periods as well as damage during flooding.
Deployment of the system is meant for rural areas and developing regions. The key to its prediction of floods
lies in the coupling of the computing model with the data acquisition system of the wireless network.

Substantial research has been carried out by Xuan, et al. in the area of early warning monitoring and
management of disasters. In their work, they have treated disaster monitoring and management as a chain of
information forming a control system. The chain consists of five modules, namely: Disaster Model Bank, Disaster
Modeling Network Link, Disaster Transmission link, Disaster Analysis, and Decision-making and Control Link.
Their model of the disaster early warning and management systems aim to demonstrate the weaknesses in present
early warning and management systems, while providing suggestions to improve the performance of these systems.
Their work aims at eliminating some of the weakest links in control loop, which will make disaster early warning
systems more reliable and efficient.

The development of the K-band receiver to receive hazard warning messages by Whistler Corporation was a
significant advancement in the initiative to increase road safety. This in-vehicle receiver works in conjunction
with a transmitter developed by the Georgia Tech. Research Institute, which sends out hazard warning messages,
e.g., emergency vehicle approaching, school bus loading or unloading.

Sharif and Hashmi have reported the use of geographical information system (GIS) and remote sensing to
detect flooding in the Indus River and its tributaries. The large volume of data associated with such a large
geographical region facilitates flood forecasting and early warning. In a related study, Cho et al. use wireless
sensor networks to remotely monitor debris flow, and have reported their technique to be very effective in
monitoring a large area with an ad hoc network.

Several structural health monitoring projects use wireless communication to facilitate coordination of devices
for more effective monitoring. The majority of these systems, e.g., are based on general-purpose sensing
platforms, which provide basic sensing functionality and accelerate development, but are largely unsuited for
long-term deployment or exposure to the elements. Other projects described in the literature, e.g., utilize
purpose-built hardware tailored to the specific needs of monitoring transportation infrastructure. The authors
of these studies have demonstrated the effectiveness of wireless sensor networks for monitoring, but unlike our
system, the systems they propose are not described as being intended for extended operations in the field, which
makes them unsuitable as a basis for the generation of safety alerts. Power consumption is high for all of the
aforementioned systems, whether or not they are based on motes. The need for battery replacement limits the unattended field life of such systems. This is a shortcoming addressed by our proposed system, which has been designed with low power consumption as a primary concern. The remainder of this paper articulates the design, implementation, and testing of our proposed alert generation system.

3. IMPLEMENTATION AND FEATURES

Implementation of the proposed road safety alert system is facilitated by the key features of the SmartBrick device - autonomy, wireless connectivity, low power consumption, long unattended field life, and physical robustness. The hardware and software of this device have been purpose-built and designed for monitoring the health and surrounding environment of a bridge or other transportation structure.\(^2\)

Figure 1 provides a block diagram of the proposed safety alert system. Motorists subscribe to safety alerts for a given region through a secure web site. The voluntary nature of this subscription mitigates privacy concerns, as no tracking is carried out to verify the location of motorists. The only information requested from the motorist is a cell phone number or email address and the locations for which he or she requires alerts. The SmartBrick communicates with the backend server of this web site twice daily, to upload data it has collected; after finishing the upload and before terminating communication, it downloads any updates to the subscriber database to its onboard memory. The database file is password-protected as a security measure. Future work on the system will include investigation of the feasibility of encrypted communication between the SmartBrick and the server.

The SmartBrick monitors the bridge (or segment of roadway) and its surrounding environment, collecting data on variables such as vibration, tilt, acceleration, temperature, and water level. A safety threshold is associated with each variable. As most other parameters of the SmartBrick, these thresholds can be remotely modified, and subsequently announced to the device through the cellular phone network. If any variable exceeds
its safety threshold, the device immediately sends an alert to the remote server, which relays the information to the subscribed motorists through the cellular network by short message service (SMS) and/or email messages. Any alerts generated are sent directly by the device through SMS to multiple designated recipients, typically authorities associated with emergency management. For email, redundant SMTP servers are used to diminish the probability of delayed deliveries. The FTP communication does not have this problem, as once the connection is established, the file is delivered directly to the remote server. Immediately after sending an alert to subscribed motorists, the server informs the SmartBrick of its action. If this acknowledgement does not arrive in a timely fashion, the SmartBrick will directly alert the subscribers. This is feasible due to storage of a copy of the subscriber database on the onboard memory of the device.

The onboard GSM module, which provides the device with long-range communication capability, is key to its role in the safety alert system. The module is a quad band GSM/GPRS modem that allows the device to communicate over the cellular phone infrastructure. It is capable of sending and receiving information by SMS, email, and FTP. This allows the system to be remotely calibrated and configured, communicate its collected data to a remote repository, and retrieve the database of phone numbers of the subscribed motorists. The ability to communicate over the cellular phone infrastructure is critical in the utility and efficacy of the proposed safety alert system. The vast majority of cellular phone users are rarely far from their handsets, and can receive text messages regardless of their location. Early warning of potentially hazardous road conditions enables them to plan an alternate route or postpone their travel. Furthermore, the system collects data and reports alert in near-real-time, facilitating timely delivery of information invaluable to traveler safety. Experimental data for communication times, as measured on the SmartBrick prototype, is presented in Section 4.

A customized operating system on the SmartBrick allows the safety alert system to operate seamlessly and with low power consumption. The operating system is designed to be simple, which minimizes code size and increases reliability, while maintaining efficient operation. A simple design also means easier debugging and troubleshooting. The software incorporates several sensing and communicating routines for polling the different sensors. The software also handles the changing of clock source, monitoring of computational loads, remote firmware updates, and communication with the serial peripheral interface (SPI) bus. The software also aids power conservation by dynamically switching the system clock based on the present computational load; it uses the lowest clock speed when the system is ready to sleep and there is no task to be executed. The operating system uses watchdog timers to prevent runaway tasks that can cause extensive power use and/or damage the system. These features of the operating system enable the SmartBrick to accomplish its key design objectives.

Autonomy is the most critical feature of the safety alert system. This is accomplished by collaboration of a 16-bit microcontroller (μC), which serves as the command center of the device, with the customized operating system, the GSM module, and the onboard sensors. This μC has several digital and analog I/O lines, in addition to multiple SPI, I2C, CAN and UART transceivers. Communication with onboard components is through the SPI bus. The μC also has several alternative clock sources, which are selected based on the performance and power consumption required. Computational tasks carried out by the μC include comparison of data (water level, tilt, vibration, temperature, humidity and battery level) collected by sensors (on the SmartBrick or its satellite sensor nodes) with safety thresholds, and generation of alerts as needed. Figure 2 depicts the main components of a standalone SmartBrick device. When satellite sensor nodes are used to increase the coverage area of the monitoring system, a Zigbee transceiver is added to the SmartBrick to enable short-range communication with these nodes. Each sensor node is very similar in structure to the SmartBrick that serves as the base station, with one significant difference: the absence of the GSM modem. The modem is the most costly component of the SmartBrick, and eliminating it from the sensor nodes achieves considerable cost savings. Communication of the sensor nodes with the outside world is through the base station, making long-range communication unnecessary for the nodes.

The SmartBrick system is designed for ultra-low power consumption, which contributes to the lengthy unattended field life and resulting autonomy of the device. The components of the power supply were selected carefully to reduce leakage currents; this aids in the longevity of system power. The power supply provides an input voltage between 4 to 6 V DC. The μC controls which system components receive power; any component not utilized in an operation can be turned off in order to minimize power consumption. Power is provided by four industrial-strength “D” cell alkaline batteries. Alkaline batteries were chosen because of their relatively long
shelf life and their ability to sustain charge substantially longer than other types of batteries. Power conservation is very important for longevity of the safety alert system, and it contributes positively to the guarantee of service to subscribed motorists.

The proposed road safety alert system is designed to be physically robust, which is required for surviving lengthy exposure to harsh environmental conditions. This is achieved by housing the SmartBrick (and any satellite nodes) in an IP 68-compliant enclosure that makes the device dustproof, rustproof, waterproof, and resistant to explosion. The enclosure is internally insulated to protect the batteries from potentially damaging temperature changes, resulting in a device that can withstand the elements during periods of no inclement weather or hazards, as well as the safety hazard conditions. Furthermore, the compact size of the device makes the system inconspicuous, which is beneficial to the system’s reliability and security. Figure 3 shows the printed circuit board of the SmartBrick and its IP 68 standard enclosure.

4. EVALUATION

The proposed road safety alert system is in the prototype stage, and has undergone successful laboratory testing that validated its ability to collect accurate data, generate alerts based on onsite or remote configuration instructions, and communicate the data and alerts to a remote server, via FTP, email, and SMS, and to designated recipients via SMS. The SmartBrick device that serves as the core of the system has undergone field testing on Bridge A6531 in Osage Beach, Missouri. Field testing was planned for the safety alert system as a whole, on a multi-span bridge in Washington County, MO. The bridge was to be designed and constructed as a collaborative research project between Missouri S&T and the Department of Transportation. Redundant instrumentation was planned for further validation of the monitoring capabilities of the SmartBrick system. Construction of this bridge has been suspended due to the current economic constraints, delaying the planned field tests.

In laboratory testing of the safety alert system, evaluation of the communication capability and power consumption was the main objective, as the monitoring capabilities of the system have been verified by previous laboratory and field tests. This section articulates the evaluation results.

In order to communicate, the GSM module, which is normally in sleep mode to conserve power, needs to be switched on and enrolled in the network. These two steps require about 25 seconds. After enrollment, an SMS
can be sent in 5 seconds, a 512-character email in 25 seconds, and a 5000-character text file, through FTP, in 30 seconds. The limitation on email length is due to the particular GSM module used. There is no limit on the amount of data exchanged by FTP. A text file of 5000 characters suffices for most situations, as numerical sensor data is compact.

Timing of the GSM transmission is affected by network conditions such as signal strength, electromagnetic noise and traffic volume in the mobile cell and the entire network. If the signal is weak, enrollment can be delayed or interrupted, while external electromagnetic noise can temporarily disrupt the communication. Traffic is also an issue, as a congested cell can prevent the device from communicating. Successful transmission of an SMS by the GSM module implies delivery to the message server, and not to the final recipient; this message server can sporadically be backlogged, delaying delivery to the final recipient. Similarly, email communication is through an SMTP server, which can delay delivery during high-traffic periods. The delay values discussed above were measured on the prototype, and reflect worst-case estimates.

Assuming no unusual delays in communication, delivery of an alert composed of SMS, email and FTP takes a total of less than two minutes from the time the device exits sleep mode. Considering that even for severe flash floods the water takes several minutes to reach a dangerous level, our device is satisfying real-time constraints.

One of the defining features of the proposed road safety alert system is its ultra-low power consumption, which is pivotal in achieving autonomy and lengthy unattended field life. Components used in the design of the SmartBrick have been carefully selected, with close scrutiny of their power consumption and leakage currents. In coordination with the operating system, dynamic scheduling and frequency scaling to significantly reduce the overall power consumption of the SmartBrick. Moreover, the device is designed to be in sleep mode by default, and is only awakened for scheduled events and alert and error situations. The success of these power-saving measures is reflected in the low current consumption of the device as it carries out the main tasks associated with communicating an alert. The current and duration measured for each task are shown in Table 1.

The total energy consumption associated with communication of an alert is 4.737 mAh, which can be considered ultra-low consumption, considering that the four “D” alkaline batteries used to power the system provide 11 Ah. This is sufficient for communication of over 2000 alerts, implying long unattended field life for the device before the batteries need to be replaced.
### Table 1. Current consumption and duration of tasks associated with communication of alerts

<table>
<thead>
<tr>
<th>Task</th>
<th>Current (mA)</th>
<th>Duration (sec)</th>
<th>Energy Consumption (mAh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Startup</td>
<td>30</td>
<td>10</td>
<td>0.083</td>
</tr>
<tr>
<td>GSM enrollment</td>
<td>150</td>
<td>25</td>
<td>1.042</td>
</tr>
<tr>
<td>Sending SMS</td>
<td>200</td>
<td>5</td>
<td>0.278</td>
</tr>
<tr>
<td>Sending Email</td>
<td>200</td>
<td>25</td>
<td>1.389</td>
</tr>
<tr>
<td>Sending FTP</td>
<td>200</td>
<td>30</td>
<td>1.667</td>
</tr>
<tr>
<td>GSM disconnection</td>
<td>200</td>
<td>5</td>
<td>0.278</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>980</strong></td>
<td><strong>100</strong></td>
<td><strong>4.737</strong></td>
</tr>
</tbody>
</table>

5. CONCLUSIONS AND FUTURE WORK

The road safety alert system described in this paper is based on the SmartBrick, a structural health monitoring device developed by the authors. Salient enabling features of the device include wireless short- and long-range communication capability, autonomy, low power consumption, and physical robustness. The system collects data, e.g., tilt and water level, about the structural health and surrounding environment of a bridge or segment of roadway. A safety threshold is associated with each parameter, and an alert is generated whenever a parameter exceeds this threshold. Alerts are communicated to a remote server, which in turn uses SMS or email to notify motorists subscribed to the service. Should the remote server fail to report successful notification of subscribers in a timely fashion, the SmartBrick directly alerts the users.

Early warning of road and bridge hazards can be instrumental in increasing the efficacy of emergency management operations and safety of the traveling public. The autonomy and low cost of the proposed system makes it well-suited to deployment in rural areas where communication of hazard information to motorists is complicated by the lack of appropriate facilities.

Future work on the system includes deployment and field testing on a multi-span bridge in Washington County, MO; improving the communication security; and linkage of the system to broadcast media such as radio and television.

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REFERENCES


